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Measurement of the scattering and absorption cross sections of the human body

Stéphane G. Conti[a]
Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, California 92037

Philippe Roux
Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093-0238

David A. Demer
Southwest Fisheries Science Center, 8604 La Jolla Shores Drive, La Jolla, California 92037

Julien de Rosny
Laboratoire Ondes et Acoustique, ESPCI, Université Paris VII, 10 rue Vauquelin, 75005 Paris, France

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Presented here are absolute measurements of the acoustic intensity scattered and absorbed by humans. The total scattering and absorption cross sections, σ_T and σ_a, were obtained for individual humans walking randomly in a room, using long-duration acoustic reverberation. Within the audible range, the sound scattering spectra of the human body is similar to that of a hard ellipsoid with same volume (dimensions proportional to the mass to the one-third power). Moreover, increasing amounts of clothing have little effect on scattering while absorption is greatly increased. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1644626]

In ancient times, drapes were hung on the very reverberant castles walls to both decorate the rooms and to reduce the echoes. Since then, most everyone has experienced the varying degree of echoes in a room with a few or many humans inside, and also with or without furniture. Despite human's longtime appreciation for the effects that objects have on the sound field in a room, the absolute characterization of their acoustic properties has been quite elusive. What is the effect of the human body on an acoustic field in the audible regime? Is absorption or scattering dominant? We present here the measurements of the acoustic scattering and absorption cross section of a human body using reverberation in a room. These measurements are of interest in understanding and modeling the effects of humans on sound, for example in the design of concert halls.

The last 15 years have seen the development of multiple-scattering imaging techniques such as diffusing wave spectroscopy[1] (DWS) for optical waves, diffusing acoustic wave spectroscopy[2,3] (DAWS)—its counterpart for acoustic waves—or coda wave interferometry[4] (CWI), the coda being defined as the scattered waves of a seismic field. Recently, DAWS has been extended to diffusing reverberant acoustic wave spectroscopy[5] (DRAWS) when multiple scattering is combined with acoustic reverberation in a cavity. Indeed, because of both scattering and reverberation, the late time arrivals of acoustic echoes from scatterers in a cavity behave in a similar way as the late coda of a multiple scattering medium.[6,7] While the purpose of CWI is to detect small changes in a medium using the strong multiscattered part of the field, DRAWS aim is the characterization of one or more moving scatterers in a stationary reverberant cavity. The advantage of DRAWS versus classical DAWS is to enable the measurement of the mean free path l of scatterers in the cavity—leading to the measurement of the total scattering cross section (σ_T)—even in the case where l is much larger than the dimensions of the cavity. The use of a reverberant cavity makes it possible to measure σ_T for a weak scatterer because the scatterer is not encountered only once by the acoustic wave, but multiple times and from multiple directions due to reverberation in the cavity. DRAWS was applied to fish for determining the number of fish in a tank,[8] or the total scattering cross section of fish[9] or krill.[10] The accuracy and precision of DRAWS in measuring σ_T was demonstrated using standard metal spheres[11] in a tank filled with water. Here, DRAWS is used to measure the scattering from the human body in the air. Also, absolute measurements of the absorption cross section (σ_a) of the human body, corresponding to the acoustic intensity absorbed by the human body, are presented here using an extension of DRAWS. The scattering and absorption measurements are related to physical and environmental parameters, such as the mass of the human and the amount of clothing they are wearing.

The experiments were conducted either in a squash court (volume 125 m^3) or a former fallout shelter (volume 31 m^3) in the audible range from 100 Hz to 3 kHz (Fig. 1). The reverberation times, T_{r60}, defined as the times when the energy density dropped 60 dB after the source is shut down,[12–14] were 5.21 and 2.38 s in the empty squash court and fallout shelter, respectively. An ensemble of M chirps $e(t)$ were emitted in the room through a loudspeaker, and the reverberation time series $h_k(t)$ sensed on multiple microphones were recorded after a time compression process, k ranging from 1 to M. One at a time, the humans walked randomly in the room, while the positions of the loudspeaker and the microphones remained unchanged. Between two consecutive pings k and $k+1$, the contribution of the room boundaries (walls, ceiling, and floor) to the reverberation time series $h_k(t)$ and $h_{k+1}(t)$ was constant, whereas the con-

[a]Electronic mail: stephane.conti@noaa.gov

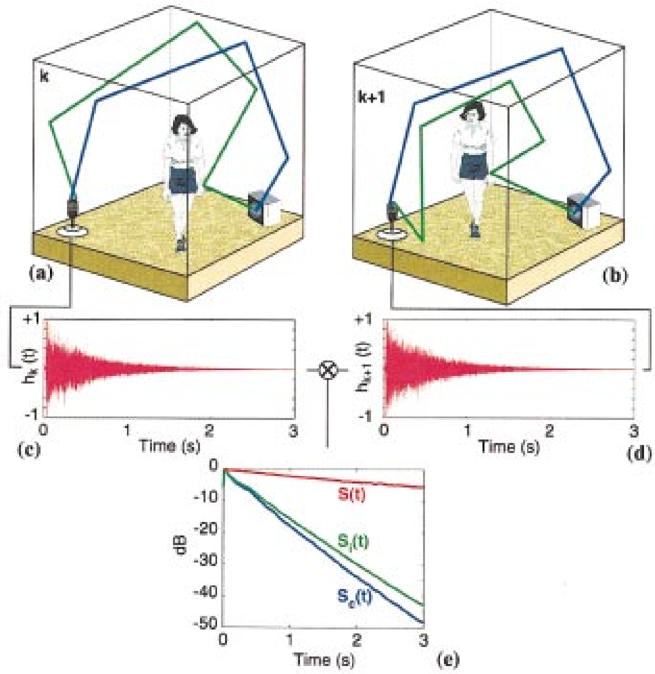

FIG. 1. (Color) The experimental setup consists of a loudspeaker and four microphones on stands placed inside a reverberant room. The signals acquisition is performed from two external soundcards (Edirol UA-5) driven by a laptop. (a), (b) Part of the acoustic field in the reverberant room has been either scattered by the human person (green ray) or by the room interfaces only (blue ray). (c), (d) From shot k to $k+1$, motion of the person leads to changes in the reverberated field (red signals). (e) The acoustic field scattered by the human body (red curve)—leading to the measurement of its scattering cross section—is obtained from the ratio of the coherent (blue curve) to the incoherent intensity (green curve). For the measurements, ensembles of $M=75$ chirps $e(t)$ were emitted and recorded using a 10 kHz sampling rate, with a 0.1 Hz repetition rate. The empty room was characterized using ensembles of $M=10$ chirps at the same repetition rate. The reverberation time series were recorded at multiple locations to average the sound field speckle.

tribution due to the human moving in the room was uncorrelated from ping-to-ping. As expected, the average signal over the pings (coherent field) decreases faster because the acoustic echoes due to the scattering from the human body vanish when averaged over many pulse repetitions. Thus, a comparison of the coherent intensity $[(1/M)\Sigma_{k=1}^{M}h_k(t)]^2$ in the room with the incoherent intensity $S_i(t) =(1/M)\Sigma_{k=1}^{M}h_k^2(t)$ provides an estimate of σ_T for each human in the room. However, the coherent intensity of the late coda may be very sensitive to small fluctuations in the medium (e.g., variant temperature)[15] during the M time-series acquisition sequence. A more robust alternative is to use the average cross products $S_c(t)=(1/M)\Sigma_{k=1}^{M}h_k(t)h_{k+1}(t)$, because the medium changes are negligible between two successive pings.

When the cavity is uniformly filled with sound ($ct \gg V^{1/3}$), de Rosny and Roux[8] demonstrated that

$$S(t)=\left\langle\frac{S_c(t)}{S_i(t)}\right\rangle \approx \exp\left(-t\frac{c}{l}\right) \approx \exp\left(-t\frac{cN\sigma_T}{V}\right), \tag{1}$$

where c is the sound speed in the air, l is the acoustic mean free path, N is the number of humans in the room, V is the volume of the room, and $\langle\,\rangle$ represents the average over the microphone positions. The last part of Eq. (1) is valid in the case of a diluted medium[16,17] which is the case when one human is present in the room. The exponential decay of $S(t)$ provides an estimate of σ_T in the frequency band of the emitted signal.

The conventional technique to estimate the absorption of sound by an object in a room is to compare T_{r60} for the room with and without the object.[12–14] Then, the absorption coefficient of the object is approximated using Sabine's formula.[14,18] Here, we measured the absolute σ_a by exploiting the motion of the target in a reverberant room. This technique can be applied to inanimate objects by providing a displacement.[11] The absorption cross section of a human in the room is estimated from the comparison of the incoherent intensity $S_i(t)$ for the room with the human inside $[S_{i\_\text{human}}(t)]$, and the empty room $[S_{i\_\text{empty}}(t)]$:

$$\frac{\langle S_{i\_\text{human}}(t)\rangle}{\langle S_{i\_\text{empty}}(t)\rangle} \approx \exp\left(-t\frac{cN\sigma_a}{V}\right). \tag{2}$$

Here again, the $\langle\,\rangle$ represent an average over the microphone positions. For measurement expediency, the emitted signals $e(t)$ were chosen to be long chirps with a wide bandwidth. The experimental noise is reduced in the reverberation time series via time compression between the received and transmitted signals. Then, values of σ_T and σ_a can be estimated either over the full bandwidth providing average values, or for narrower frequency bands within the full bandwidth using band pass filtering, leading to the spectra $\sigma_T(f)$ and $\sigma_a(f)$.

Thus, σ_T and σ_a were measured between 1 and 2 kHz for 27 people including children and adults. The childrens' and adults' ages, masses, and heights ranged from 3 to 55 years old, 17.7 to 95.5 kg, and 1.02 to 1.95 m, respectively. Each human is modeled as an ellipsoid of revolution whose small radius is a characteristic length a and the height of the ellipsoid is $L=\alpha\, a$. Knowing that the volume of the ellipsoid is defined as $\vartheta=M/\rho=2\pi\alpha a^3/3$, it follows:

$$a=\left(\frac{3}{2\pi}\,\frac{M}{\alpha\rho}\right)^{1/3}, \tag{3}$$

where M is the human mass and ρ is the density of the human body. For humans, reasonable values are $\alpha=11$ and $\rho=910\ \text{kg m}^{-3}$. Using this model, the characteristic length a depends on the human mass only, irrespective of its height. The acoustic measurements show a linear relationship between σ_T and the characteristic length a squared (Fig. 2). The average cross section of the human body seen from all possible incidence angles is then proportional to $M^{2/3}$. As the 27 humans were wearing similar amounts of clothing, σ_a is weaker than σ_T and also seems to be proportional to the body surface.

The dependence of the total scattering cross-section with frequency $\sigma_T(ka)$ was estimated for six humans from 100 Hz to 3 kHz, where $k=2\pi f/c$. The humans' ages, masses and heights ranged from 3 to 24 years old, 17.7 to 66 kg, and 1.02 to 1.8 m, respectively. The spectra were rescaled with the high frequency scattering limit $\sigma_{T\infty}$ for the ellipsoids corresponding to each human.[19] The spectra $\sigma_T(ka)/\sigma_{T\infty}$ are consistent for all six humans (Fig. 3), even if some variations between the spectra can be observed due to shape differences between the humans. The average empirical scattering spec-

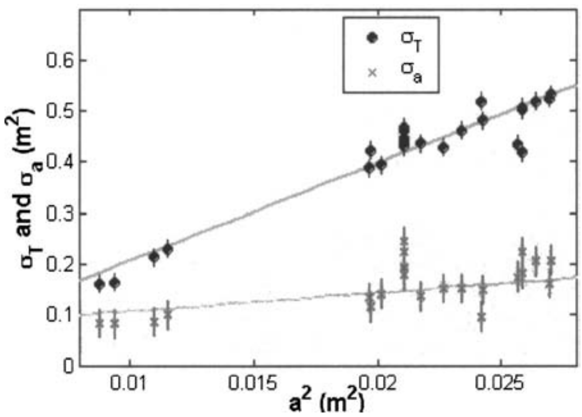

FIG. 2. Total scattering cross section σ_T and absorption cross section σ_a for 27 humans, measured from 1 to 2 kHz, vs the characteristic length a squared. σ_T and σ_a increase linearly with a^2, but σ_a is weaker than σ_T.

trum for humans is similar to the spectrum for a hard ellipsoid (Fig. 3). For a hard ellipsoid, $\sigma_T(ka) \approx \sigma_{T\infty}$ when $\lambda \ll 2\pi a$, where $\sigma_{T\infty}$ is the maximum total scattering cross section for the ellipsoid. Therefore, scattering from a human in air can be compared to that of an ellipsoid having equivalent radius a and length $L = \alpha\ a = 11a$.

As already shown (Fig. 2), σ_a does not change significantly with the different humans wearing similar clothing. The effects of clothing on σ_T and σ_a were characterized through a sequence of 18 measurements on a single human (66 kg, 1.8 m, 24 years old) wearing different amounts of clothing. Garments ranged from underwear to multiple layers of winter clothing and pieces of foam. The results of this experiment (Fig. 4) show that σ_T does not change significantly with the amount of clothing on the human, whereas σ_a increases dramatically with the amount of clothing, starting at a negligible value of 3.10^{-3} m^2 for the human in underwear, and rising up to 0.86 m^2 with maximum clothing. Clothes behave as an artificial layer of low acoustic impedance in which sound is trapped and finally lost. However, the amount of clothing does not significantly change the surface of the human body in a first approximation, and therefore does not affect its scattering cross section.

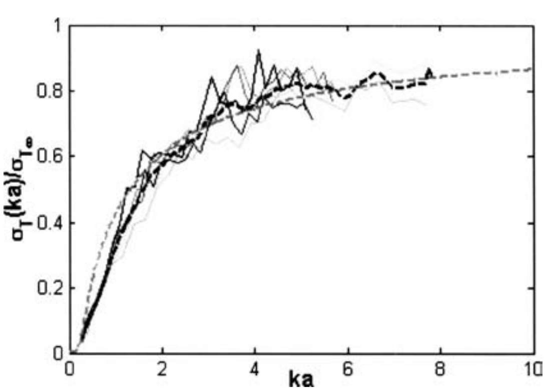

FIG. 3. Total scattering cross-section spectra $\sigma_T(ka)/\sigma_{T\infty}$ for six humans (solid gray lines; the darker the line, the lighter the human), measured in the shelter from 0.1 to 3 kHz and rescaled in ka domain with $k = 2\pi f/c$ and $\alpha = 11$. The average of the empirical human total scattering cross-section spectra is presented in dashed black. The dashed gray line corresponds to the scattering spectra for a hard ellipsoid in air, with a density $\rho = 910$ kg m^{-3}, and a total length $L = \alpha\ a = 11a$.

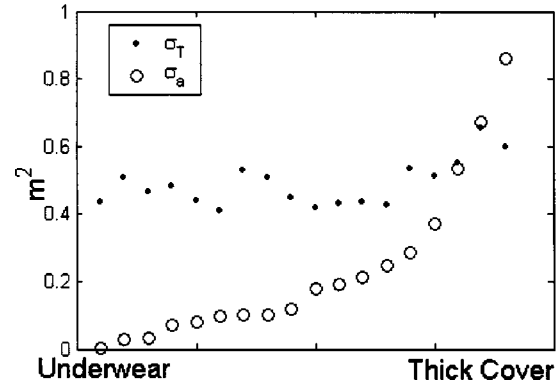

FIG. 4. Total scattering cross section σ_T and absorption cross section σ_a for one human wearing different amounts of clothing. σ_T is constant with the increasing amount of clothing, whereas σ_a increases significantly.

In conclusion, we have demonstrated that the scattering of sound from the human body is solely described by the mass of the human, while the absorption is largely dominated by the amount and type of clothing. That is, the human body scatters sound, but does not significantly absorb sound because it behaves as a rigid scatterer filled with water; the converse is generally true for clothing. The influences of a human on the sound field in a room can be compared to that of a hard ellipsoid with the same volume, and a length to radius ratio of 11, and density $\rho = 910$ kg m^{-3}, wrapped in a weakly scattering layer of absorbing material.

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[1] P. E. Wolf and G. Maret, Phys. Rev. Lett. **55**, 2696 (1985).
[2] M. L. Cowan, J. H. Page, and D. A. Weitz, Phys. Rev. Lett. **85**, 453 (2000).
[3] M. L. Cowan, I. P. Jones, J. H. Page, and D. A. Weitz, Phys. Rev. E **65**, 066605 (2002).
[4] R. Snieder, A. Grêt, D. Huub, and J. Scales, Science **295**, 2253 (2002).
[5] J. de Rosny, P. Roux, M. Fink, and J. H. Page, Phys. Rev. Lett. **90**, 094302 (2003).
[6] J. de Rosny and M. Fink, Phys. Rev. Lett. **89**, 124301 (2002).
[7] R. Hennino, N. Trégourès, N. M. Shapiro, L. Margerin, M. Campillo, B. A. van Tiggelen, and R. L. Weaver, Phys. Rev. Lett. **86**, 3447 (2001).
[8] J. de Rosny and P. Roux, J. Acoust. Soc. Am. **109**, 2587 (2001).
[9] S. G. Conti and D. A. Demer, ICES J. Mar. Sci. **60**, 617 (2003).
[10] D. A. Demer and S. G. Conti, ICES J. Mar. Sci. **60**, 625 (2003).
[11] D. A. Demer, S. Conti, J. De Rosny, and P. Roux, J. Acoust. Soc. Am. **113**, 1387 (2003).
[12] A. D. Pierce, *Acoustics, An Introduction to Its Physical Principles and Applications*, 2nd. ed. (Acoustical Society of America, New York, 1989), pp. 250–312.
[13] P. M. Morse and K. U. Ingard, *Theoretical Acoustics* (Princeton University Press, Princeton, NJ, 1986), pp. 576–599.
[14] L. L. Beranek, *Acoustical Measurements* (Acoustical Society of America, New York, 1988), pp. 781–791.
[15] A. Tourin, A. Derode, and M. Fink, Phys. Rev. Lett. **87**, 274301 (2001).
[16] A. Ishimaru, *Wave Propagation and Scattering in Random Media* (Oxford University Press, New York, 1997), p. 253.
[17] P. Sheng, *Introduction to Wave Scattering, Localization, and Mesoscopic Phenomena* (Academic, San Diego, 1995), Chaps. 3 and 4.
[18] W. C. Sabine, *Collected Papers on Acoustics* (Dover, New York, 1922), p. 103.
[19] R. D. Spence and S. Granger, J. Acoust. Soc. Am. **23**, 701 (1951).